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Behavior of pile due to combined loading with lateral soil movement

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Abstract

Piles are commonly used to transfer vertical forces, arising primarily from super structure. Lateral loads, however, are just as important as vertical loads in designing pile foundations and are often more complicated. More powerful lateral loads occur as a result of unpredicted events such as heavy wind, earthquakes, slope failure, and lateral spread induced by liquefaction. But in actual case combined action of vertical and horizontal ground loads can occur in many situations for a pile. So the study of combined load behaviour of soil is important. But these all are suitable only in horizontal ground only. If the pile is in sloped ground then the behaviour of a pile is not only depend on the combined loading but also depends on the lateral soil movement due to the effect of slope. So in this paper by using finite element software, the behaviour of a pile due to the combined loading is studied along with and without the influence of lateral soil movement is made. The effect of the lateral soil movement is depends on the slope angle, so for this study varying slope angles (1:1, 1:1.5 and 1:2) were also considered.

Keywords: Horizontal ground, Sloped ground, Combined load, Lateral soil movement, Varying slope angle (1:1, 1:1.5 and 1:2), FE model

Background

Piles are commonly used to transfer vertical forces, arising primarily from super structure. But for some structures, the primary function of pile is to transfer the lateral loads to. But in many places in addition with the vertical forces, piles are also transferring the lateral forces due to heavy wind, earthquakes, slope failure, and lateral spread induced by liquefaction. So the combined action of vertical and horizontal ground loads can occur in many situations for a pile. So the study on the behaviour of pile with lateral and combined loading is an important. Begum [1] conducted an experimental study of laterally loaded pile on sloped surface by varied the slope angles. This experimental study is also used to develop a graphical non dimensional relationship between the lateral load and maximum bending in a pile. Begum and Muthukkumaran [2] conducted an experimental study of laterally loaded pile on sloped surface by varied the slope angle (zero slope, 1:1.5 and 1:2), L/D ratio (25, 30 and 35) and the relative densities of the soil (30, 45 and 70 %). Broms [3] developed solutions for the ultimate lateral resistance of a Pile assuming the distribution of lateral soil pressure and considering static of the problem and also two modes of failure and yielding of the soil along the length of the Pile were considered. Abbas et. al. [4] used to model a single Pile in layered soil by using PLAXIS-3D

(FEM software) and compared the lateral load carrying capacity between circular Pile and square Pile. In addition, an effect of slenderness ratio L/B is carried out and also discussed about the negative base deflection of Pile. Judi et al. [5] presented a series of three dimensional numerical analysis performed by FLAC3D finite difference program on solid concrete piles with circular section in clayey soils under combination of axial and lateral loading. Karthigeyan et al. [6] used 3-dimensional finite element program GEOFEM3D, to analyse the combined loading on pile in both sand and clayey soil. Lee et al. [7] presented a simplified approach for the study of a row of piles used for slope stabilization in both homogeneous and non-homogeneous soil profiles. Begum and Muthukkumaran [8] studied the behaviour of a pile due to the lateral load on sloped surface and for this study pile is considered at crest of the sloped surface. So in the field of analysis of pile due to combined load was not well explored. So in this paper, the behaviour of pile due to combined load is focussed on both and sloped grounds (1:1.5, 1:2 and 1:2.5). Muthukkumaran et al. [9] conducted the experimental study on aluminium pile in the sloped sandy soil surface with varying density. Muthukkumaran et al. [10] conducted the experimented study on behaviour of pile due to the varying surcharge load on sloped surface and this study was made in soil have different relative densities (30, 45 and 70 %). Poulos [11] modeled pile-soil interactions using elastic continuum methods that consider the soil to act as a 3-D, linearly elastic, homogeneous, isotropic, semi-infinite medium. Used Mindlin's equations to develop factors that account for additional displacements (αp) and rotations ($\alpha \theta$) caused by interactions from adjacent piles. Poulos and Davies [12] modified the elastic solution to account for nonlinearity using yield factors. The modulus of subgrade reaction approach was extended to account for the soil nonlinearity.

Mesh details

Figure 1 shows a schematic 2D finite-element mesh for analysis of pile-soil interaction in both horizontal and sloped grounds. The pile is analysed for plane strain condition. 15-noded soil elements were used, so the corresponding interface elements are defined by five pairs of nodes. The interface elements are shown to have a finite thickness, but in the finite element formulation the coordinates of each node pair are

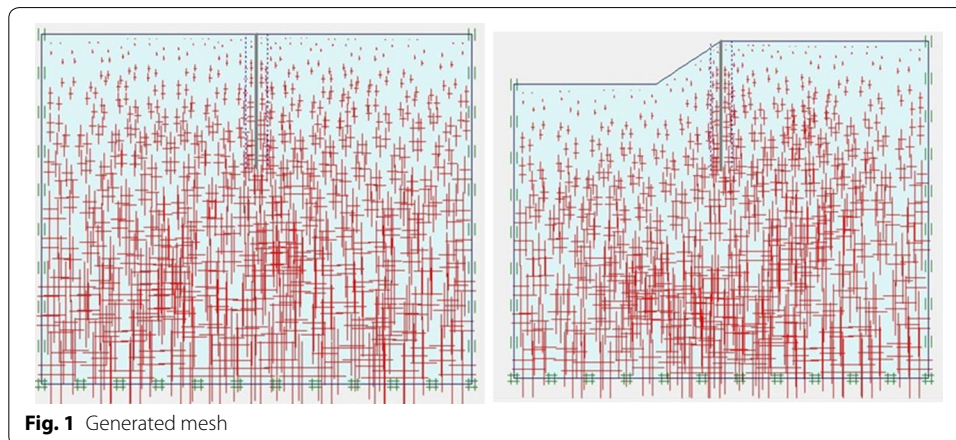


Table 1 Soil details

| Soil details | Sandy |
|-----------------|----------------------|
| Cohesion | 0 |
| Friction angle | 36° |
| Dilation angle | 6° |
| Young's modulus | 50 Mpa |
| Poisson's ratio | 0.3 |
| Unit weight | 20 kN/m ³ |

Table 2 Pile details

| | |
|------------------------|-------------------------------------|
| Normal stiffness (EA) | 2.83×10^7 kN |
| Flexural rigidity (EI) | 2.54×10^6 kNm ² |
| Diameter of pile | 1.2 m |
| Length of pile | 18 m |
| Type of pile | Concrete |
| Grade of concrete | M ₂₅ |
| Poisson's ratio | 0.15 |

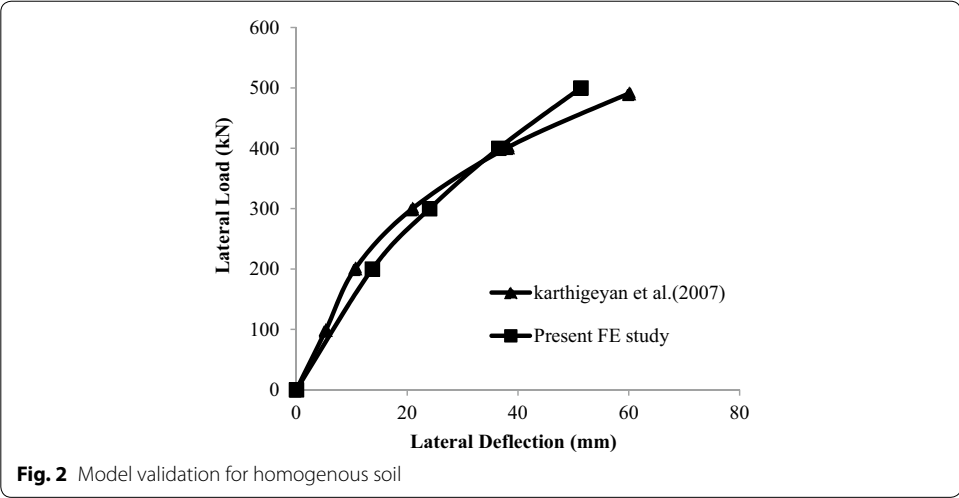
identical, which means that the element has a zero thickness. The distances to lateral rigid boundaries in the finite-element analyses are shown in Fig. 1. All the nodes in the mesh were having the boundary conditions as created by the standard fixities option, as a result of which the program generates full fixities at the bottom and vertical rollers at the vertical sides. The number of nodes, interface elements in the mesh will vary according to the variation of pile length and diameter.

Pile-soil details

Plate elements in the two-dimensional finite element model are composed of beam elements (line elements) with three degrees of freedom per node (two translational degrees of freedom and one rotation). The pile is represented by a five noded beam-column element (Winkler's theory). This theory allows for beam deflection due to shearing as well as bending. In addition, the element can change length when an axial force is applied. Bending (flexural rigidity) stiffness EI and axial stiffness EA are the input values. The analyses are conducted with homogenous sand, represented by Mohr–Coulomb model. The properties considered for the soil is taken from the Karthigeyan et al. [6], as shown in Tables 1 and 2 represents the properties of pile.

Analysis scheme

The model with homogeneous layer of soil and pile is created. Interface is created around the pile. Boundary conditions are assigned to the model. Standard fixity is provided to the model. Material properties given in Tables 1 and 2 are assigned to the model. Then mesh is generated. Region around the pile is refined for mesh generation. In this case, water table is assumed at the ground level. Initial water pressure and initial effective stress are generated. Then analysis is done. Now, plastic calculation is done and the pile is activated. This type of problems is generally simulated using a plane strain model.

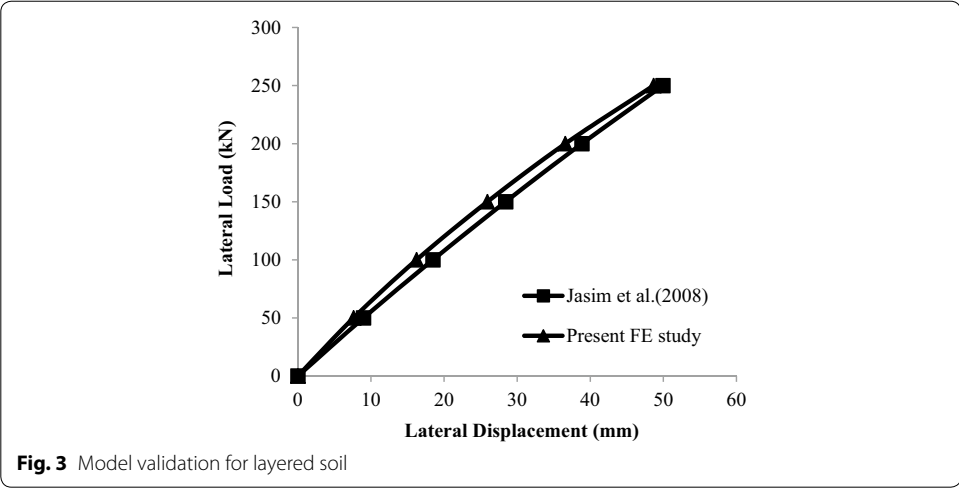


Validation of the numerical model

The validity of the numerical model employed in the program was verified by predicting the response of the piles under pure lateral load from two different published cases, one with respect to homogenous kind of soil and the other with a different layered soil stratum. The details of these two validations are presented in the following sections.

Validation for homogenous soil

Karthigeyan et al. [6] performed a series of 3D finite-element analyses on a single free-headed pile in homogenous sandy soils. The response of the piles under pure lateral load was analysed. For this purpose the case of lateral load alone acting on the pile was considered. The analysis in the lateral direction was performed using displacement control (rather than load control) so that the lateral loads developed at various lateral displacement levels could be evaluated as a percentage of the pile diameter. The reaction forces developed at the nodes were used to calculate the lateral load corresponding to the applied lateral displacements. Figure 2 shows the comparison between present FEM and



literature results. From the figure it is clearly seen that the present FE model is very well matching with literature results.

Validation for layered soil

Abbas [4] performed 3D finite-element analysis on the behaviour of single pile under lateral loadings in non-homogenous soils. The pile of circular cross-section was used for the analysis and the loads were at the head of the pile. The loading consists of small amount of loading which is 50 kN in the beginning of loading stages. The investigation continues to reach a maximum amount of loading that always using in the design of piles when subject to a lateral load. Figure 3 shows the comparison of layered soils. The FE model is also very much matching with the layered soil result.

Parametric studies

A series of 2D finite-element analyses were performed on a single free-headed pile in homogenous sandy soil created on both horizontal and sloped grounds (1:1.5, 1:2 and 1:2.5). The soil properties and the dimensions of the pile considered in these analyses are reported in Tables 1 and 2. The response of the piles under pure lateral load and combined action of both lateral and axial load condition were analysed. The analysis in the lateral direction was performed using load control so that the lateral displacements developed at various lateral load levels could be evaluated as a percentage of pile diameter. The maximum lateral deflection in case of constant diameter pile was limited to 120 mm (i.e., 0.1D as per Karthigeyan et al. [6]).

Results and discussion

Influence of lateral load on pile head in the sandy soil

Figure 4 represents the lateral load carrying capacity of pile on both horizontal ground (zero slope) and the sloped grounds having different slope angles (1:1.5, 1:2 and 1:2.5). From the data presented it is noted that as the slope angle increases, the lateral load carrying capacity of the pile will get decreased and the pile at horizontal ground having

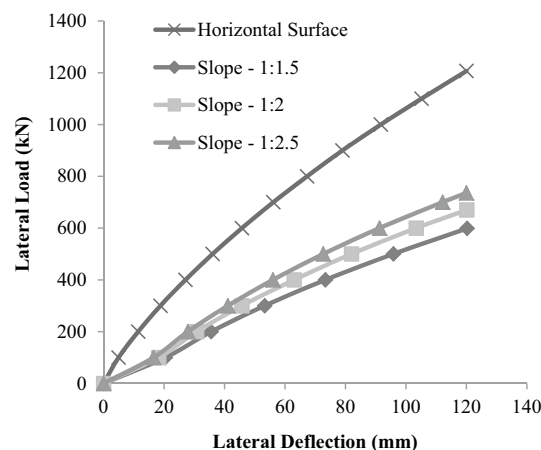


Fig. 4 Lateral load on Pile head at both horizontal and sloped grounds

higher lateral load carrying capacity when compared with pile at sloped ground. The reason for this variation of lateral capacity of the pile is due to the lateral confinement of the soil around the pile. It can be also explained as when the pile is on a horizontal ground, it is fully confined with the soil but it is not the case on a sloped ground. So due to the lateral load, the soil in horizontal ground can offer more resistance to the pile which is not present for the pile on a sloped ground. Figure 4 also represents that the pile at the slope of an angle 1:2.5 was having more lateral load carrying capacity than the pile at other sloped grounds of an angle 1:2 and 1:1.5. If the slope angle increases then the lateral load carrying capacity of the pile is getting decreased. This can be explained as, for the increase in slope angle the mass of failure soil at the sloped ground is more and hence it will make additional lateral load to the pile. So, it can be concluded that the load carrying capacity of pile will decrease with increasing slope angles.

Influence of combined load on pile head in the sandy soil

Figure 5 represents the effect of combined load on the pile head in the sandy soil at the horizontal ground. Figures 6, 7 and 8 represents an effect of combined load on the pile head in the sandy soil at the sloped ground with slopes of 1:1.5, 1:2 and 1:2.5 respectively. For this study an axial load of 2500 kN is divided into 0, 20, 40, 80 and 100 % and is applied individually over a pile head with varying lateral load.

From the result shown in Fig. 5, due to axial load the lateral load carrying capacity of the pile is increased in the sandy soil. This can be explained as the heavy axial load acting on the pile head creates fixity condition for the pile and hence reduces the lateral deflection of the pile head. Also due to angle of internal friction (ϕ) the lateral load carrying capacity gets increased. Compared to sloped ground, the effect of a settlement is less on horizontal ground in the combined loading condition.

From the result shown in Figs. 6, 7 and 8, the lateral load carrying capacity of pile in sandy soil due to combined loading on a sloped ground also gets increased but it is until a certain axial load limit only. Beyond that it gets decreased. This can be explained as the effect of settlement is high in sloped ground than the horizontal ground. Due to axial load, there is no lateral displacement of pile in horizontal ground, but it occurs on a sloped ground. Due to combined loading the lateral load carrying capacity of pile in sloped ground is high in slope angle 1:2.5 and low in slope angle 1:1.5. So if the slope angle is going steep, an additional lateral force is offered by the soil mass, it results in decrease in the load carrying capacity of pile.

Influence of settlement of pile in the sandy soil

Figures 9, 10 and 11 represents the settlement of a pile on both horizontal ground (zero slopes) and sloped ground (1:1.5, 1:2 and 1:2.5) due to the axial load at the pile head and the results are as shown. This is because the effect of a settlement is more on a sloped ground (1:1.5, 1:2 and 1:2.5) than on a horizontal ground (zero slope). On the sloped ground with slope 1:1.5 was having more settlement than the other two sloped grounds (1:2 and 1:2.5) and the sloped ground 1:2 was having more settlement than the sloped ground 1:2.5. This is because, as the slope gets steeper, the lateral soil movement will also get increased. Hence, the steeper sloped ground (1:1.5) has more settlement than the other sloped grounds (1:2, 1:2.5 and zero slope).

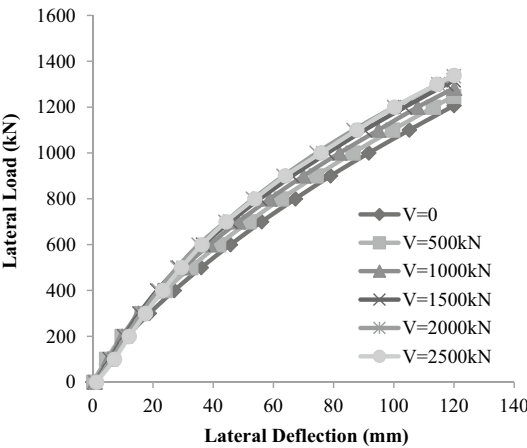


Fig. 5 Combined load on Pile head at horizontal ground

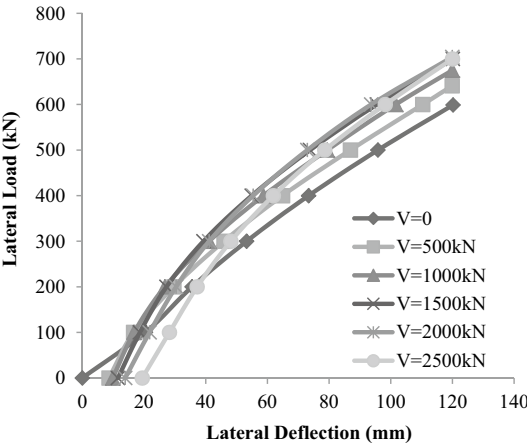


Fig. 6 Combined load on pile head at sloped ground 1:1.5

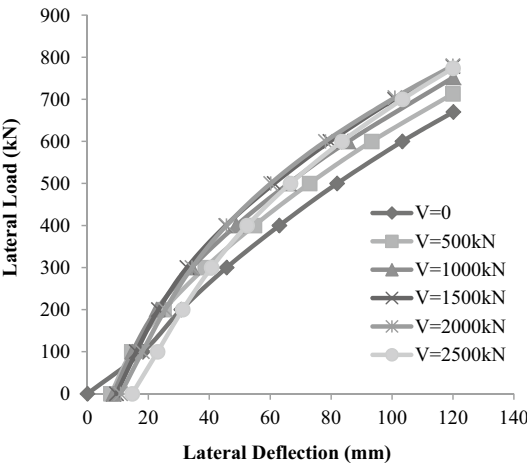
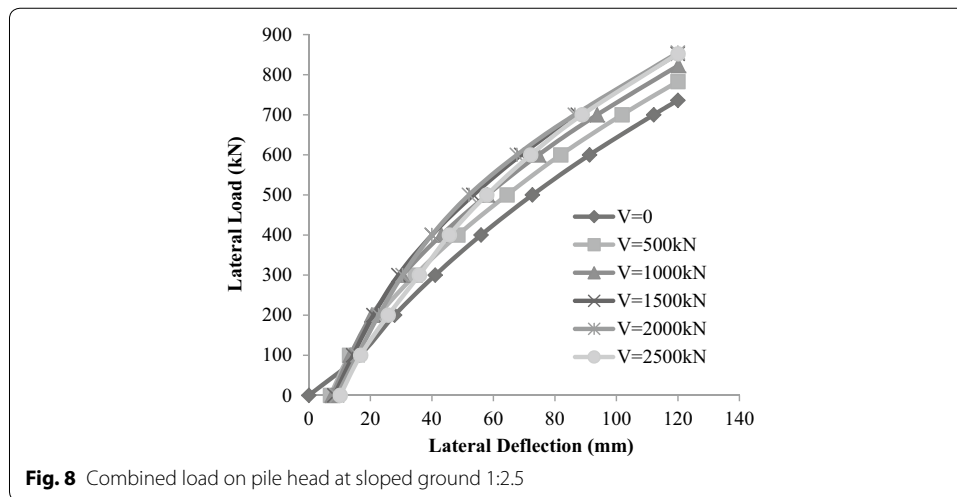


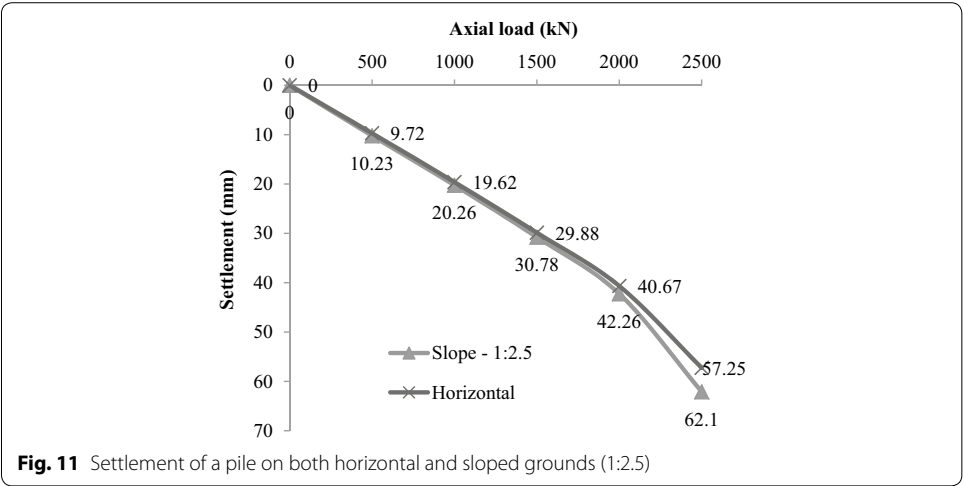
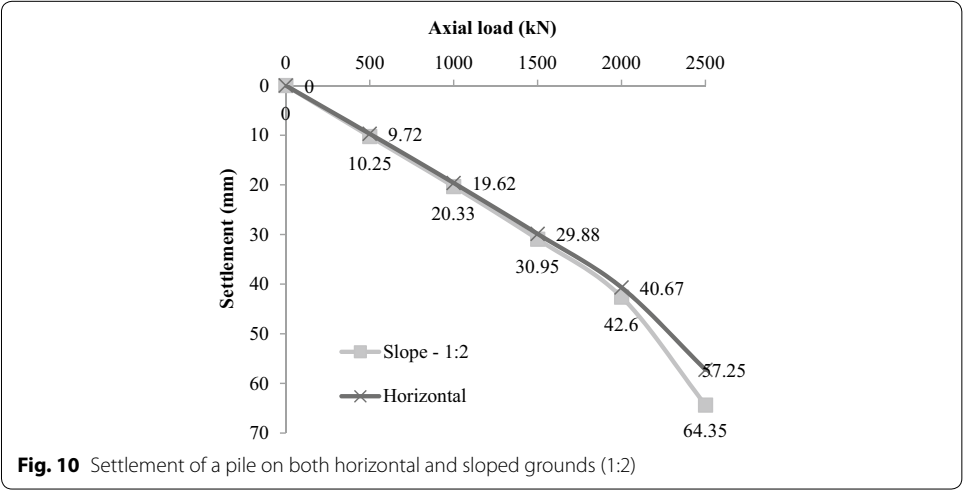
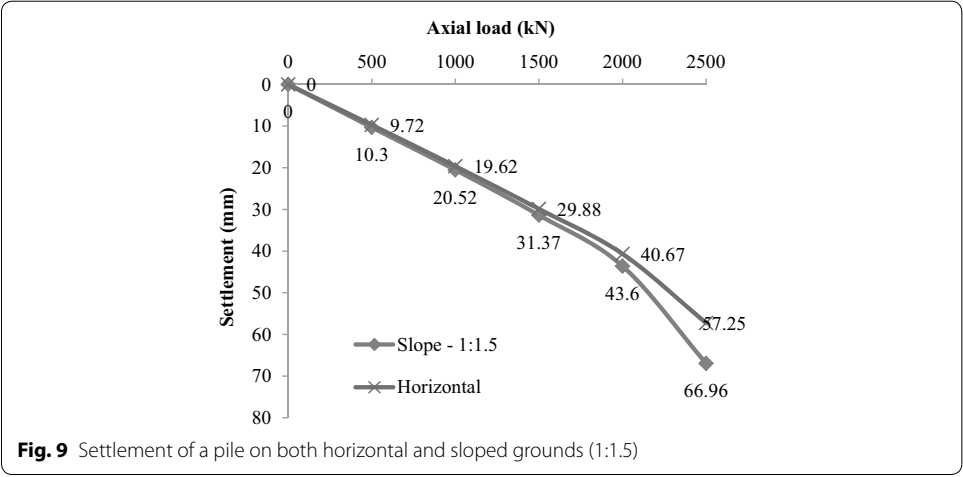
Fig. 7 Combined load on pile head at sloped ground 1:2



Conclusion

The study captures the behaviour of pile subjected to lateral, combined loading in homogenous sandy soil profile, the lateral deflection being limited to 120 mm. The following conclusions can be made:

- Significant lateral deflection was observed for pile subjected to axial load on a sloped ground while it was insignificant on a horizontal ground.
- The lateral load carrying capacity of a pile is decreasing with increase in slope angle. The decrease in capacity was 50.37, 44.49 and 39.02 % for slope of 1:1.5, 1:2 and 1:2.5.
- Due to combined loading, the lateral load carrying capacity of a pile is increasing in the sandy soil on horizontal ground.
- On horizontal ground, a pile subjected to lateral load has a capacity of 1207 kN. The lateral load carrying capacity increased by 3.31, 6.29, 9.11, 10.6 and 10.9 % when combined with an axial load of 500, 1000, 1500, 2000 and 2500 kN.
- Due to combined loading, the lateral load carrying capacity of a pile is increasing in the sandy soil on horizontal ground.
- On horizontal ground, a pile subjected to lateral load has a capacity of 1207 kN. The lateral load carrying capacity increased by 3.31, 6.29, 9.11, 10.6 and 10.9 % when combined with an axial load of 500, 1000, 1500, 2000 and 2500 kN.
- For combined loading on sloped ground (for certain slope), the lateral load carrying capacity increases until certain limit and later it starts to decrease due to the settlement effect.
- For a slope of 1:1.5, a pile subjected to lateral load has a capacity of 599 kN. The lateral load carrying capacity increased by 7.01, 12.6, 16.86 and 17.53 % when combined with an axial load of 500, 1000, 1500 and 2000 kN. But when combined with an axial load of 2500 kN, the lateral load carrying capacity dropped down to 16.86 %.
- For a slope of 1:2, a pile subjected to lateral load has a capacity of 670 kN. The lateral load carrying capacity increased by 6.42, 12.2, 16.12 and 16.41 % when combined



with an axial load of 500, 1000, 1500 and 2000 kN. But when combined with an axial load of 2500 kN, the lateral load carrying capacity dropped down to 15.52 %.

- For a slope of 1:2.5, a pile subjected to lateral load has a capacity of 736 kN. The lateral load carrying capacity increased by 6.38, 11.82, 15.76 and 16.16 % when combined with an axial load of 500, 1000, 1500 and 2000 kN. But when combined with an axial load of 2500 kN, the lateral load carrying capacity dropped down to 15.76 %.
- The increase (%) in lateral load capacity when combined with increasing axial loading is more for higher sloped ground when compared with the increase (%) in capacity for increasing axial load on a lesser sloped ground.
- The effect of settlement of pile is more in sloped ground surface than the horizontal ground.

Authors' contributions

In this entire research work was carried out by BJ, but without a support of Dr. KM, completion of this research work was not possible. In this paper, the main work of BJ was FEM model and based on the model results only, the conclusions were made. Dr. KM was shared his knowledge at every stages of this paper, especially at the conclusion part. Both authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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